Ultra-high efficiency solar cells: the path for mass penetration of solar electricity

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For achieving a photovoltaic penetration above one-third of the world demand for electricity in the first half of this century, the importance of a fast manufacturing learning curve that is linked to the capacity of developing cells of increasing efficiency is stressed. Progress in multi-junction cells is described as well as three novel concepts promising very high efficiency. It is explained why these concepts will probably be used in concentrator systems.

Introduction: The world is facing the big challenge of sustainability. Perhaps, more than one billion inhabitants will achieve the consumption patterns of the First World in the next decades. This will place stresses on many resources and, in particular, the need for a sustainable energy supply is no exception. In addition, the CO_2 emission of our present energy transformation processes, based mainly on burning fossil fuels, is possibly the main cause of global climatic change. The photovoltaic conversion of solar energy is a clean way of producing electricity with high land-occupation efficiency (e.g. as compared to biomass), which for sustainability should (and most probably will) become a major source of electricity

Photovoltaics (PV) is today growing explosively. From 1996 to 2004 it grew annually at a rate of over 33% compared to 6.3% for the semiconductor industry as a whole. The growth became even faster, up to 69%, in 2007 . However, a model developed by one of us, that takes into account the PV module learning curve (how much the price is reduced each time the production doubles) and the demand elasticity (how the price influences the market, which is defined as the negative logarithmic derivative of the market with respect to the price) allows for forecasting the evolution of markets and prices. The model has been shown to be accurate in the last nine years after its implementation (see Fig. 1). It has been extrapolated to 2050 with certain assumptions concerning the evolution of the elasticity. The challenge is for PV to generate over one-third of the world electricity consumption by 2050 [7].

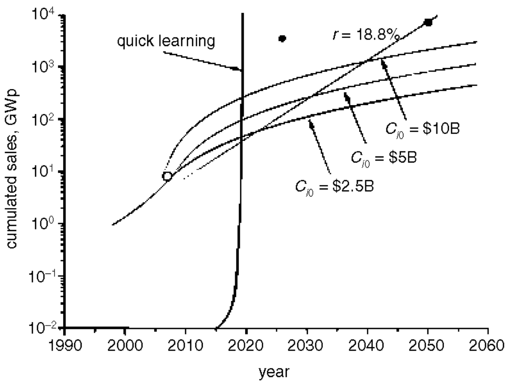

Fig. 1 *Cumulative PV installations for different capital availability (C_{i0})*

C_{i0} = \$10B, \$5B, and \$2.5B represent 0.1, 0.05 and 0.025% of the gross domestic product (GDP) of industrialised countries. 'Quick learning' plot has learning factor (price reduction when cumulative fabrication is doubled) of 0.68. For the rest, the learning factor is 0.8253. Hollow dot represents cumulated market at present. The solid dots represent the cumulative sales that would be required to supply 22% by 2025 and 34% by 2050 of the world electricity consumption Factor r = 18.8% represents the constant growth rate that would permit desired goal to be reached by 2050 (presently it is higher)

The model is only applicable for studying the onset of the competitive situation and not its subsequent development. When PV electricity reaches a price that is competitive with the prevalent electricity generation price, the model produces a vertical asymptote. This is a model artefact because the model considers the potential market to be infinite.

With the historic learning curve, which is usually deemed constant for a certain technology without major changes, PV is expected to become an important industrial branch although its penetration will remain modest. However, if we set in the model the learning factor of semiconductor memories, the price of competence would be achieved a few years after this new technology enters into the market (after a cumulative penetration of 10 MW).

We think that the reason for the slow learning curve of the silicon-dominated photovoltaic industry lies in the fundamental efficiency limitations of any single junction solar cell . Actually, only the photons with energy slightly above the bandgap are effectively converted. The photons of less energy are not absorbed and of the photons of higher energy, only the bandgap energy (actually this value times the Carnot factor) at most, can be recovered. After all, the sun is a huge resource but relatively diluted and it is reasonable to expect that only high-efficiency extraction can be cost effective for mass exploitation.

The multijunction and concentrator approaches: Conceptually, the most trivial way to circumvent the efficiency limits associated with single junction solar cells is to fabricate a stack of different cells with different bandgaps. Fig. 2 shows an outline of a triple junction solar cell. It consists of three cells connected in series by means of tunnel junctions, all fabricated epitaxially on a germanium wafer. The most energetic photons are absorbed in the top solar cell, of higher bandgap (1.80 eV, 688 nm , less energetic photons are absorbed in the middle solar cells (1.28 eV, 968 nm), and finally, the remaining photons until the Ge bandgap edge (0.69 eV or 1800 nm) are absorbed in this semiconductor. Few photons are in the solar spectrum below this energy.

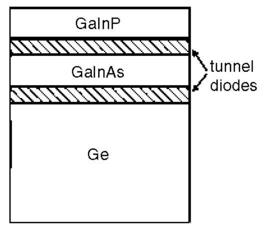

Fig. 2 *Outline of epitaxial triple junction solar cell*

So far, the best efficiency achieved in a monolithic epitaxial cell is 40.7% [10] operating at 240 suns (24 W/cm^2). Efficiencies of 42.8% have been announced [11] in a very complex rig using optical elements, and six junctions over four substrates. Since the biggest part of the cell cost is that of the substrate, we consider this result less interesting.

In the full monolithic approach, Ge is used as the substrate because it has almost the same lattice constant as GaAs. However, concentrator cells are more robust to imperfections because they operate at higher voltages where favourable photovoltaic fundamental mechanisms tend to prevail. In consequence, the bandgaps can be better adjusted by adding In to the GaAs and departing a bit from the Ge lattice constant. The record efficiency has been obtained for a cell with $Ga_{0.92}In_{0.08}As$ and $Ga_{0.44}In_{0.56}P$.

In the USA roadmap of multijunction (MJ) solar cell development, it is planned to have a 45% four-junction cell by 2009. So far, this roadmap has been fulfilled. Thus, there is today a frantic search for a solar cell in the range of 1 eV, but it has remained elusive until now. In general, the materials found have too low a mobility. After this, the efficiency-rising potential of this concept might be perhaps exhausted, but novel concepts may come along to pave the way towards higher efficiencies.

The MJ solar cells we described are very expensive, above \$10 000/m^2 This cost is prohibitive for competitive energy production. However, if we operate them with a concentration of say, 1000 suns, the cost will be reduced approximately by the same factor, that is, to \$100/cm^2. This cell cost, if accompanied by a 33.3% overall efficiency and 1000 W/m^2 of standard irradiance, leads to a Wp cost of \$0.3/W, compared with the current cost of \$3/W of a silicon module (of course, we have to add the cost of the concentrator).

Solar cells can be operated at this concentration and higher MJ concentrator cells are small. The present record cell area is 0.267 cm^2 Other cells are of 0.01 cm^2 and this helps to bring the top efficiency to around 700 suns, although at 1000 suns the decrease of efficiency is small (also for the record cells).

Concentrators are a key part of these PV systems. They require a sun-tracking structure and it is a challenge to make them with the needed accuracy at low cost, more so for high concentration. Today a good efficiency for the optics is 80%. Efficiency losses could be reduced with proper antireflection coatings and laser quality reflectors, but constraints on the cost make this difficult. Furthermore, only a fraction of the available sun energy is direct sunlight, which is the only one collected by the concentrator optics. In good climates this fraction can be 80%.

However, dozens of companies consider that there is a bright future in MJ concentrator panels (visit, for instance, the website of the recent Concentrated Photovoltaic Summit'08, http://www.cpvtoday.com/). In June 2006 and 2007 two international call for tenders were issued in Spain for a total 3 MW of PV concentrator plants and seven companies have been selected (three from Spain, two from the USA, one from Germany and one from Taiwan). This is possibly the first attempt to promote industrial manufacturing of MJ concentrators.

Flat modules, without moving parts, are much better integrated in buildings than concentrators but it will be difficult to reach the level of penetration needed–one-third of the world's electricity–using only this solution. The density of the urban population in most of the world (excluding those living in family houses) is too high to allow their supply of electricity only from solar panels installed where they live. But if we compare the moving concentrators with this case, in many clear climates more direct radiation is collected on a tracking plane than global radiation falls on a stationary plane latitude tilted facing the South (in the Northern hemisphere), thus reducing the disadvantage of not collecting the diffuse light.

The new concepts: Shockley and Queisser established, based on detailed balance grounds, the limiting efficiency for the single junction cell Recently extensive attention has been paid to developing concepts that can exceed this limit in some cases as a result of workshops where high level specialists met by invitation. published by the USA DOE, Office of Basic Science, three novel concepts were considered under the heading 'Revolutionary photovoltaic devices: 50% efficient solar cells': the intermediate band (IB) solar cell, the multiexciton generation solar cell and the hot carrier solar cell.

As shown in Fig. 3, an IB solar cell is formed from an IB material situated between two ordinary semiconductors—*n*- and *p*-type, respectively—that play the role of selective contacts to the conduction band (CB) and valence band (VB) electrons. The IB material has a band of states inside the bandgap between the CB and the VB that should be partly filled with electrons. In this way, photons with less energy than the one necessary to pump an electron from the VB to the CB (process 3 in Fig. 3) can be absorbed by transitions that pump an electron from the VB to the IB (process 1) and from the IB to the CB (process 2). Thus, a full VB → CB electron transition (or electron–hole pair generation) can be completed by means of two photons of energy below the bandgap. This mechanism should increase the solar cell current.

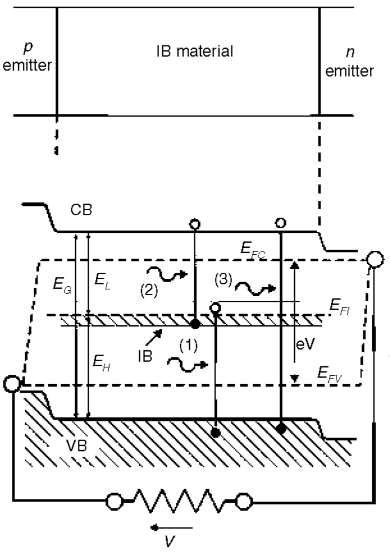

Fig. 3 *Plot explaining basic structure and operation of intermediate band solar cell*

However, any increase in cell current achieved through the reduction of the bandgap photon absorption threshold (say, from E_G to E_L in Fig. 3) is usually accompanied by a reduction of the voltage. To avoid this, it is necessary that three separate quasi-Fermi levels (QFLs) appear in the IB material, two of them associated with the CB (E_{FC}) and VB (E_{FV}), as in ordinary solar cells, and the third one associated with the IB (E_{FI}). The voltage extracted from the cell is precisely the difference between the CB and VB QFLs at the *n*- and *p*-contacts, respectively (change of sign and divided by the charge of the electron). By allowing the existence of these three quasi-Fermi levels and as appreciated again from the plot in Fig. 3, the output voltage is still limited by the total bandgap E_G and not by the sub-bandgaps E_L or E_H. However, photons of lower energy than this voltage can contribute to the current thanks to the IB, which is not the case in ordinary solar cells.

The limiting efficiency of this concept for maximum concentration (the one providing isotropic illumination on the cell with the radiance of the sun's photosphere) is 63.2% compared with the Shockley-Queisser limit of 40.7% for an ordinary cell in the same conditions.

GaAs IB cells have been fabricated using the confined levels of InAs quantum dots (QD) to form the IB. Experimental evidence of the electron–hole formation through the described two-photon mechanism has been found In addition, a separation of three quasi-Fermi levels has been experimentally found for cells direct biased However, the efficiency is not higher than that of the cells without quantum dots mainly because of the low current enhancement because of the weak absorption in the QD, due to their inherent low density ($<10^{17}$ cm^{-3}) and low IB material thickness (0.1 μm). Intermediate band solar cells based on alloys, with higher density ($>10^{19}$ cm^{-3}) of sub-bandgap photon-absorbing centres, could solve this problem.

Levels situated in the middle of the gap, also called deep levels, are known to be introduced by certain impurities and to act as effective centres of SRH recombination. In this respect, it is important to make a clear distinction between deep levels and an IB. The difference lies in the density of the impurities. When it is high enough to suffer a Mott transition, the electrons become delocalised, the deep level becomes an impurity band and the SRH recombination is thought to disappear IB has been identified in several compounds using photoreflectance techniques.

IB cells can be put in stack among themselves or together with ordinary cells. It is predicted that two IB cells connected by a tunnel junction have the potential to give almost the same energy as a six-junction MJ solar cell [27].

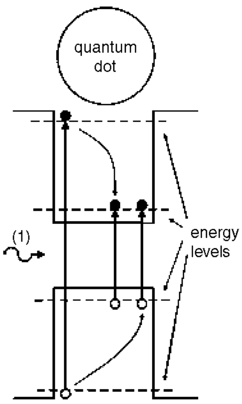

Fig. 4 *Illustration of multiple exciton generation mechanism in quantum dots*

Two other concepts for ultra-high efficiency solar cells are the multiple exciton generation (MEG) solar cell, which attempts to create more than one electron–hole pair from photons with enough energy to do so A schematic of the mechanism is presented in Fig. 4. In this concept, the excitation of a high-energy electron–hole pair created after the absorption of a high-energy photon (photon 1) produces the generation of several electron–hole pairs. Up to seven electron–hole pairs have been generated by a single photon in PbS quantum dots This device seems to be especially interesting for the low bandgap range

The other concept is the hot carrier solar cell (Fig. 5) in which the energy of non-thermalised electrons created by high-energy photons (photon 1) is intended to be utilised In this concept, the electron–phonon interaction should be greatly reduced. Once this is achieved, the electrons become hot and their energy is extracted by energy selective contacts. These contacts allow only those electrons with high energy tunnel towards the metal electrodes. A Fermi level splitting of the electrons in these metals is produced, which then appears as an output voltage. The potential efficiency of the two last concepts is very high (above 85.4 %)

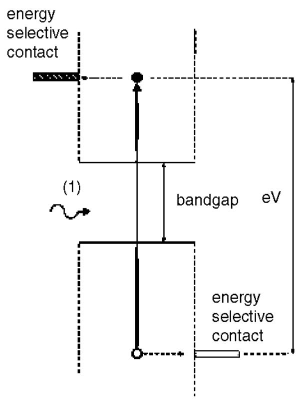

Fig. 5 *Illustration of operation of hot carrier solar cell*

Conclusions: We believe that PV can generate one-third of the world's electricity demand by the middle of this century, but for this the present technology has to experience radical changes leading to a learning curve faster than the present one by converting the solar energy with much higher efficiency. It may be this breakthrough is already occurring. MJ cells are developing their high efficiency potential. Other high efficiency concepts are still incipient, but we expect that, when associated in stacks with ordinary or novel cells, they will allow a climb of efficiency to above the 50% target. The use of concentrators will be necessary to render the highly sophisticated cells cost competitive. Nevertheless, the situation seems to be ripe for their industrialisation and this will make it possible to liberate cell research from the cost constraints that have so far hindered their development.

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